CORROSION FATIGUE BEHAVIOR OF COATED 4340 STEEL FOR BLADE RETENTION BOLTS OF THE AH-1G HELICOPTER

MILTON LEVY and JOSEPH L. MORROSSI
METALS RESEARCH DIVISION

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ABSTRACT

The main rotor blade bolt for the 540 helicopter rotor system of the AH-1G, UH-1C, and UH-1M helicopters is proposed to be improved by substituting plasma-sprayed tungsten carbide coating on the outer shank of the 4340 steel bolt for the present cadmium or chromium plate. This study was undertaken to determine the effects of these coating systems on the fatigue behavior of 4340 steel in environments likely to be encountered in service. Both axial tension-tension and rotating bending fatigue testing of coated specimens were carried out in air and in 3.5% NaCl solution. The NaCl environment causes reductions in fatigue strength of bare and coated 4340 steel. The severity of the degradation depends on the coating applied and the type of fatigue test utilized.

INTRODUCTION

The main rotor blade bolt for the 540 rotor system (AH-1G, UH-1C, UH-1M helicopter) is proposed to be improved by the substitution of plasma-sprayed tungsten carbide (WC) coating on the outer shank for the present cadmium (Cd) or chromium (Cr) plate. The WC coating was originally suggested to reduce the costly machining and plating operations required to recondition blade retention bolts for the AH-1G helicopter. Fretting-induced corrosion resulted in significant surface pitting on the bolts after less than 500 hours of service. Based on prior results with a similar configuration bolt for the 240 rotor system, a WC-coated bolt is expected to last over 3000 hours as compared to 300 hours for current Cd-plated new production bolts and about 500 hours for Cr-plated reworked bolts. A cost savings in excess of $100,000 per year has been projected if bolt reconditioning and replacement were eliminated.

Although WC-coated bolts for the 240 rotor system have not experienced any fatigue problems, the U.S. Army Aviation Systems Command Value Engineering decided that coating effects on fatigue life should be investigated prior to approval of the WC coating for the following reasons: (1) the blade retention mechanism is subjected to fatigue conditions due to steady centrifugal loading; (2) stress analysis of the blade retention bolt provided no assurance that the part was not fatigue critical; (3) available data on the effect of the WC coating on the fatigue strength of 4340 steel was inadequate;[1,2] (4) the need for utilizing the Coricone sealer in conjunction with the WC coating for enhanced corrosion resistance had not been confirmed. This study was undertaken to determine the effects of these coating systems (WC, Cd, Cr) on the fatigue behavior of 4340 steel in environments likely to be encountered in service. In addition, the efficacy of the Coricone sealant (for enhanced corrosion resistance) in combination with the WC and the solid film lubricant was also determined. Full-scale axial fatigue tests of the coated blade retention bolts were carried out by AMRDL-Langley Research Center, Va., and the data obtained are reported elsewhere.[3]

MATERIALS

The substrate alloy (bolt material) was VAR 4340 steel. Axial tension-tension and rotating beam fatigue specimens were rough machined (turned) and heat treated according to the following schedule: normalized at 1650 F for 1 hour; air cooled; austenitized at 1525 F for 1 hour; oil quenched (130 to 170 F); tempered at 900 F for 4 hours directly from the oil quench before reaching room temperature. The ultimate tensile strength of the alloy was 194 ksi. The fatigue specimens were subsequently finish machined (turned and polished to 8-16 rms finish), shot peened, and the following coating systems applied:

1. Cd plating plus chromate treatment
2. Cr plating plus solid film lubricant (SFL)

1. VIGLIONE, J., JANKOWSKY, E. J., and KETCHAM, S. J. *Effects of Metallic Coatings on the Fatigue Properties of High Strength Steels.* Materials Protection and Performance, v. 11, March 1972, p. 31-36.
2. LEVY, M., and MORROSSI, J. *Erosion and Fatigue Behavior of Coated Titanium Alloys for Gas Turbine Engine Compressor Applications.* Army Materials and Mechanics Research Center, AMMRC TR 76-4, February 1976.
3. LEVY, M., and SWINDLEHURST, C. E., Jr. *Evaluation of Tungsten Carbide Coated Blade Retention Bolts for the AH-1G Helicopter.* WASA TM in process.

3. Plasma-sprayed WC plus solid film lubricant with Coricone and
4. Plasma-sprayed WC plus solid film lubricant without Coricone.

Detailed coating procedures are shown in Table 1. Coating thickness requirements are contained in Table 2. The coated test specimens were fatigue tested (both axial tension-tension and rotating bending) in air and 3.5% sodium chloride solution (to simulate marine atmosphere). Fatigue testing of the bare 4340 alloy was also carried out to obtain base-line data.

EXPERIMENTAL PROCEDURES

Fatigue Tests

Rotating Bending Fatigue: Stress versus cycles-to-failure studies of smooth fatigue specimens were carried out using a Krouse rotating bending fatigue

Table 1. COATING PROCEDURES

a. Cadmium Plating (0.0003-0.00049 in. Cd)	1. Degrease and rinse in flowing water 2. Cyanide dip 30 to 60 sec at RT 3. Cd plate at 20 amps/sq ft 4. Rinse in water 5. Bake at 385 F, minimum 23 hours (within 1 hour of plating) 6. Degrease 7. Cyanide reactivation - 5 to 10 sec at RT 8. Rinse in water 9. 15 to 20 sec in chromate conversion bath 10. Rinse in water and dry
b. Chromium Plating (2-2.5 mil Cr)	1. Degrease and rinse in flowing water 2. Reverse etch in chromium plating bath (131 F) 3. Cr plate 131 F 4. Rinse 5. Bake at 375 ± 25 F for minimum of 3 hours 6. Dip plated samples into solid film lubricant (MIL-L-46010) 7. Air dry for 30 minutes at RT 8. Cure at 400 F for minimum of 1 hour (SFL thickness 0.35 mil)
c. Plasma-Sprayed Tungsten Carbide Plating	1. Grit blast fatigue specimens according to MIL-A-21380B 2. Plasma spray WC-Co (METCO 72F-NS) 7 to 9 mil per side 3. Surface grind to 3.25 to 4.0 mil per side 4. Apply Coricone 1700 sealant by spraying - 0.2 mil per side (specimens were prepared with and without Coricone) 5. Dry at RT 6. Cure at 350 F for at least 20 minutes 7. Dip specimens into SFL (0.35 mil per side) 8. Air dry for 30 minutes at RT 9. Cure at 400 F for minimum of 1 hour

Table 2. THICKNESS OF COATINGS

Cadmium	0.3 - 0.5 mil/side
Chromium	2.0 - 2.5 mil/side
Tungsten Carbide (After Finish Grind)	3.25 - 4.0 mil/side
Coricone Sealer	0.2 mil/side
Dry Film Lubricant	0.35 mil/side

machine. The fatigue apparatus was operated at 3000 rpm, which is equivalent to a cyclic stress reversal frequency of 50 Hertz and a stress ratio $R = -1$. The standard Krouse fatigue machine was modified by the addition of a Lucite environmental chamber for corrosion fatigue studies, as shown schematically in Figure 1. A Schaar Sigmamotor tubing pump delivered the test fluid through Tygon tubing from a two-liter reservoir at the rate of 15 liters per hour. The pulsations of the pumping system were removed in a settling chamber, so that a steady stream of fluid would flow over the test section of the fatigue specimen. The fluid was then returned to the reservoir by gravity flow. At speeds up to 3000 rpm, the fluid maintained good contact with the rotating specimen as it flowed over and around the test section.

Rotating bending fatigue specimens measured 1/2" diameter by 5" long, with a 2" radius reduced section giving a minimum cross section of 1/4" diameter at the specimen center. Stressing of the specimen was accomplished using a sliding weight to apply a bending moment. A counter kept track of the number of stress cycles, and a limit switch shut off the machine at specimen failure. Run-out cycle count was 10^7 cycles.

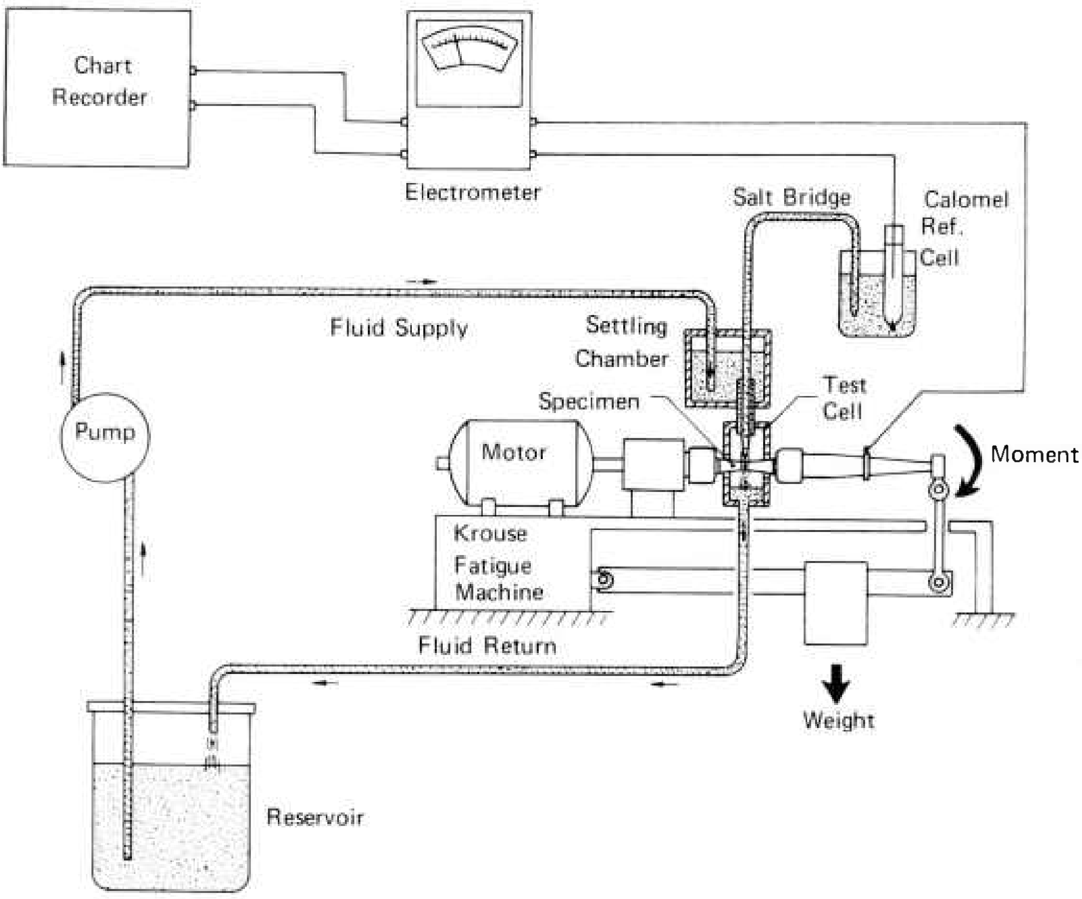


Figure 1. Schematic for corrosion fatigue apparatus.

Axial Tension-Tension Fatigue Test

Fatigue testing of axial tension-tension smooth fatigue specimens was carried out using the Instron Dynamic Cycler Model 1211 system and sinusoidal loading. The apparatus was operated at 2000 rpm which is equivalent to a cyclic frequency of 33 Hertz and a stress ratio R = 0.8. For tests in 3.5% NaCl solution, a plastic cell containing this environment was attached to completely surround the gage length of the specimen. Unlike the corrosion cell of the rotating bending fatigue apparatus, the solution was quiescent. Axial tension fatigue specimens measured 1/2" diameter by 3" long, with a 1-1/2" radius reduced section giving a minimum cross section of 0.200" diameter at the specimen center.

RESULTS

Rotating Bending Fatigue

Figure 2a shows the deleterious effect of NaCl solution on the fatigue life of bare 4340 steel. The fatigue strength (value at 10^7 cycles) of the bare specimen decreases from 105 to 20 ksi, a reduction of 81%. Figure 2b contains S-N curves for the 4340 steel coated with electroplated cadmium plus chromate treatment. The air value of the bare material is identical to that of the coated material (105 ksi). Parallel to data for steels in general, the fatigue limit of the bare alloy in air is approximately one half the tensile strength. The NaCl solution reduced the fatigue strength of the coated alloy by 24% (from 105 ksi to 80 ksi). If we compare the fatigue strength of the coated alloy in NaCl solution with that of the bare alloy in the same environment, it is apparent that the cadmium plus chromate treatment significantly improves the fatigue strength of the alloy in NaCl solution (from 20 to 80 ksi). Figure 2c shows that 3.5% NaCl solution caused a 5.3% reduction in the fatigue strength of 4340 steel coated with electroplated chromium plus solid film lubricant (from 95 to 90 ksi). This coating system produced a 9.5% degradation in the fatigue life of the bare steel (Table 3) in air. The fatigue strength of the alloy coated with plasma-sprayed tungsten carbide plus solid film lubricant with or without the Coricone sealant was 90 ksi regardless of the environment (Figure 2d, Table 3), i.e., there was neither a deleterious effect of environment nor a beneficial effect of the Coricone sealant. A fatigue reduction of 14.3% was attributed to the coating system.

Axial Tension-Tension Fatigue

Figure 3 contains S-N curves obtained in air for the alloy, bare and coated. Fatigue data at 10^7 cycles showed that the cadmium and chromium electroplates, particularly the chromium, improved the fatigue strength of the bare alloy. The tungsten carbide coating reduced fatigue strength from 160 to 140 ksi which represented a fatigue reduction of 12.5%. The Coricone sealant had no effect on fatigue strength of the alloy in air. Table 3 contains fatigue data at 10^7 cycles for the uncoated and coated alloy in 3.5% NaCl solution. This environment caused a 31.2% reduction in the fatigue strength of the bare alloy and a 45 to 60% reduction in the fatigue strength of the WC-coated alloy and the Cr-plated alloy. The Coricone again provided no beneficial effect on the corrosion fatigue resistance of the WC-coated alloy. The Cd-plated alloy was unaffected by the

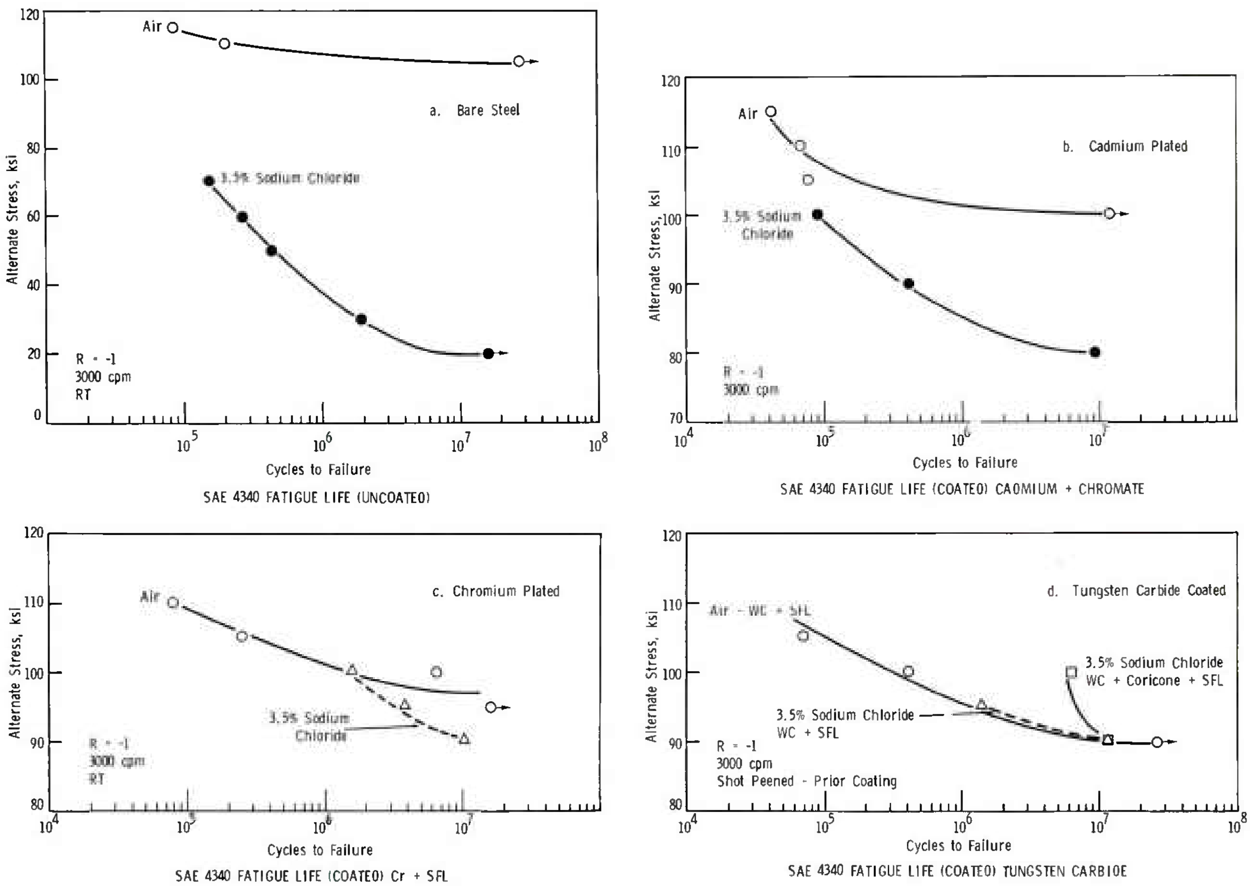


Figure 2. S-N curves (rotating bending) of 4340 steel showing effect of environment.

Table 3. EFFECTS OF COATINGS AND ENVIRONMENT ON THE FATIGUE STRENGTH OF 4340 STEEL (UTS 180 TO 200 KSI)

Test	Condition	Air Stress, ksi	Air Reduction, %	3.5% NaCl Stress, ksi	3.5% NaCl Reduction, %
Rotating Bending[1]	Bare	105	-	20	-81
	Cd + Chromate	105	-	80	-24
	Cr + Dry Film*	95	-9.5	90	-14.3
	WC + Dry Film*	90	-14.3	90	-14.3
	WC + Coricone + Dry Film*	90	-14.3	90	-14.3
Axial Tension[2]	Bare	160	-	110	31.2
	Cd + Chromate	165	+3.1	165	0
	Cr + SFL*	175	+9.4	90	43.8† 48.6‡
	WC + SFL*	140	-12.5	60	62.5† 57‡
	WC + Coricone + SFL*	140	-12.5	60	62.5† 57‡

*Shot peened
†Compared to bare alloy air value
‡Compared to coated alloy air value
1. R = -1, 3000 cpm; fatigue life 10^7 cycles
2. R = 0.8, 2000 cpm; min. stress/max. stress

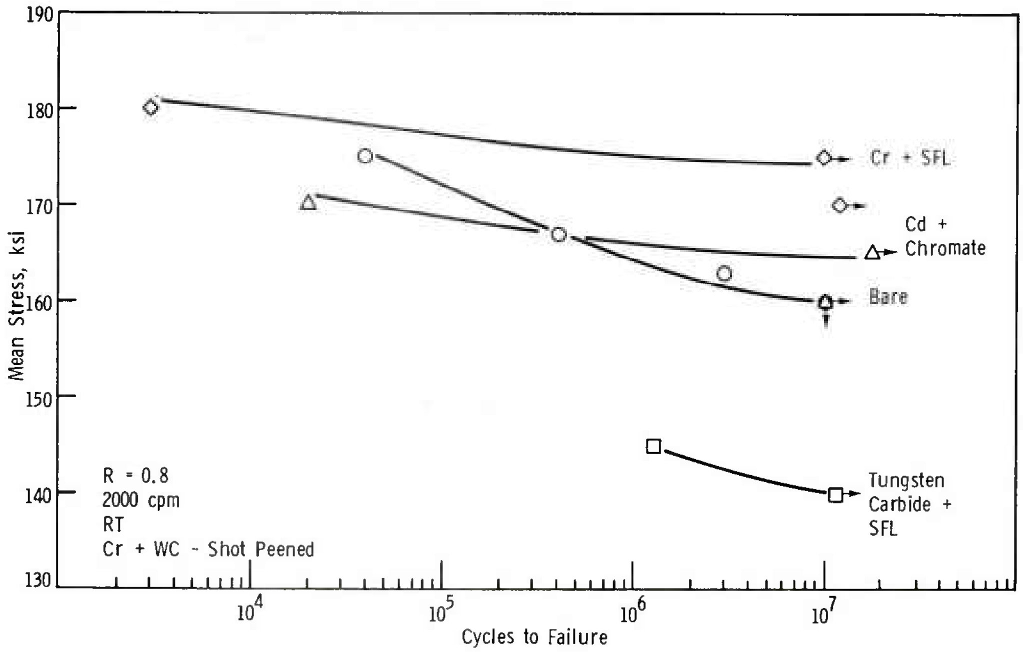
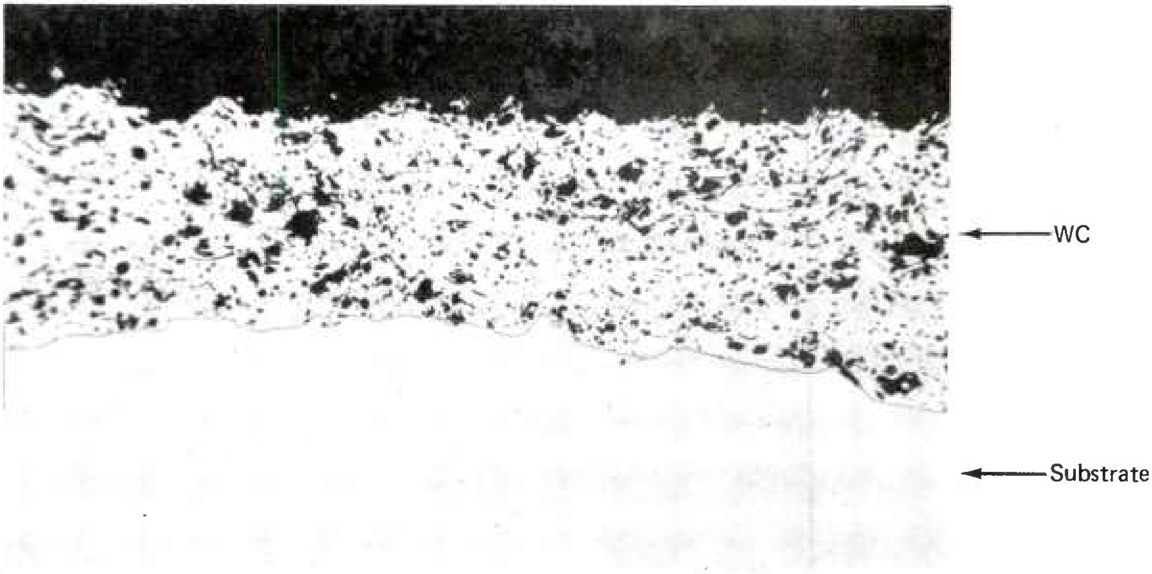


Figure 3. Bare and coated SAE 4340 axial tension fatigue life air-media.

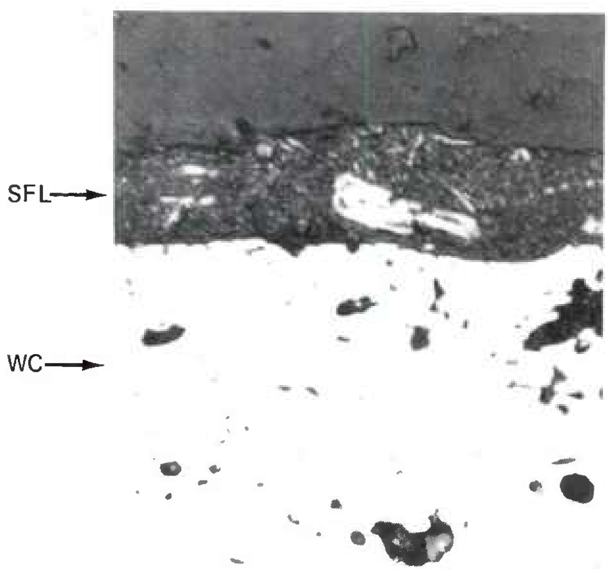
NaCl solution. It is evident that the axial tension fatigue data differs from the rotating bending fatigue data in the following manner: (a) degradation of fatigue strength of the bare alloy due to NaCl solution is considerably less in axial tension; (b) NaCl solution causes significantly greater reductions in axial tension fatigue strength for both the WC-coated alloy and the Cr-plated alloy. However, based on air values only, fatigue strength reductions due to the coatings were quite similar in both rotating bending and axial tension fatigue tests.

Metallography

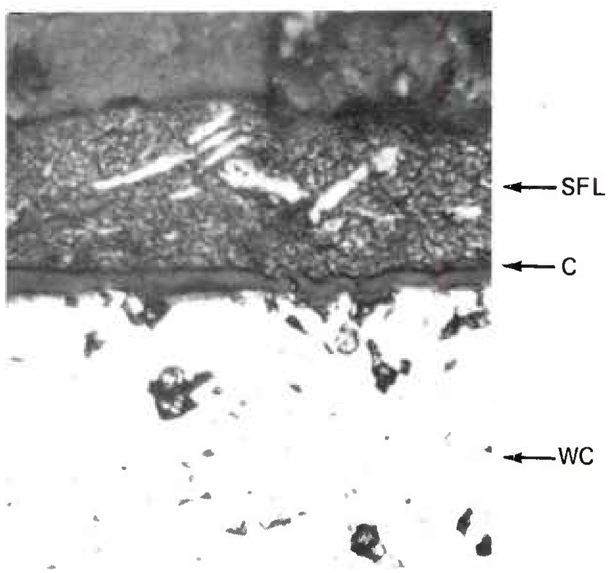
The WC-coated specimens were examined metallographically for an assessment of coating integrity, bonding, and the sealing capability of the solid film lubricant and Coricone. Figure 4 contains micrographs of the cross-sectional area of the coated specimens. Figure 4a demonstrates the good bonding between plasma-sprayed WC and the substrate 4340 steel. Note that some porosity is present and that the pores are discontinuous. Figure 4b shows good bonding between the solid film lubricant and the WC coating. Also shown is the capability of the SFL to fill surface pores present in the WC coating. Figure 4c demonstrates the good bonding that can be obtained between SFL and Coricone and between Coricone and WC coating. Note that the Coricone has filled any surface pores present in the WC coating. Since the pores in the WC coating are discontinuous, neither the SFL nor Coricone has infiltrated below the surface pores.



a. Tungsten carbide coating/substrate interface. Mag. 200X



b. Solid film lubricant/tungsten carbide coating interface. Mag. 1000X



c. Solid film lubricant/Coricone/tungsten carbide interface. Mag. 1000X

Figure 4. Micrographs of cross-sectional area of plasma-sprayed tungsten carbide coating interfaces.

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CONCLUSIONS

1. NaCl solution significantly degrades fatigue strength of the bare 4340 steel. The degradation is much more severe under conditions of rotating bending fatigue.

2. Although the fatigue strength of WC-plus-SFL-coated 4340 steel is unaffected by NaCl solution in rotating bending fatigue, it is significantly reduced by this environment in axial tension fatigue testing. Regardless of the method of testing, the Coricone sealant does not impart additional resistance to corrosion fatigue and the WC coating reduces the air fatigue strength of the 4340 steel by about 14%.

3. NaCl solution further degrades the rotating bending fatigue strength of both Cd- and Cr-plated 4340 steel, but in axial tension fatigue testing, further degradation is limited to the Cr-plated alloy.

4. Regardless of the method of test, the sprayed WC and the plated Cr coatings exhibit comparable fatigue behavior in NaCl solution.

5. Despite the reduced fatigue strength of the WC-coated steel, full-scale fatigue tests of the blade retention bolts (carried out at AMRDL-Langley) produced no failures through the equivalent of four life-times (approximately 14,000 flight hours of loading). Note that the full-scale component fatigue tests were carried out in laboratory air.

6. Rigorous inspection procedures for rotor blade bolts should be followed, particularly after operations in marine environments. It is recommended that inspection of the WC-coated blade retention bolt be made after 250 hours of operation, or at a lesser time if in consonance with inspection of a neighboring component.

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